k_T Asymmetry in Longitudinally Polarized $p + p$ Collisions in PHENIX

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Abstract. We examine the helicity dependence of partonic transverse momentum k_T derived from di-hadron azimuthal correlations in longitudinally polarized $p + p$ collisions in PHENIX data from RHIC Run 5. The motivation is to explore the possible contribution of partonic orbital angular momentum to the measured intrinsic k_T as described in [1]. We follow the analysis procedure described in [2] that relates the width of the away-side peak in the azimuthal two-particle distributions to the total transverse momentum of the di-jet. The asymmetry of $\Delta \sqrt{\langle k_T \rangle} = 672 \pm 387$ MeV/c is found to be large, but with limited statistical significance.

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Being the lowest energy baryon state, one would, with good foundation, expect that the quarks which make up the proton would be in an s-state. The naive expectation then, is that there is no orbital angular momentum contribution to the proton spin. However, measurements of the quark spin contribution to the proton spin, ($\Delta\Sigma$), have determined that only a small fraction of the proton spin is due to quark polarization [3, 4, 5, 6, 7, 8, 9, 10]. Recent measurements of ΔG, the gluon polarization inside the proton, are still statistically limited but have excluded large values of gluon polarization [11, 12, 13]. Forthcoming data from RHIC should place tighter constraints on ΔG, and perhaps will solve the spin-puzzle. However, progress in the quark and gluon spin distributions has rekindled interest in orbital angular mometum. In fact, it has been shown recently [14] in a model independent way, that the proton anomalous magnetic moment *requires* orbital angular momentum of the quarks, although *net* orbital angular momentum may be zero.

The history of the theoretical interest in orbital angular momentum inside hadrons can be traced to a paper by Chou and Yang in 1976 [15] describing hadronic matter current inside a polarized hadron. Later, Meng Ta-chung et al., [1] proposed two experiments to access hadronic matter currents, one in semi-inclusive deep inelastic scattering of unpolarized leptons on transversely polarized protons, and the second in the measurement of the net pair transverse momentum of Drell-Yan pairs in collisions of longitudinally polarized protons. It is the latter which lays the theoretical basis for this analysis.

In the late 1990's, Ji proposed a method to access *quark* orbital angular momentum [16] via what he referred to as Deeply-Virtual Compton Scattering. Several groups have persued this experimentally challenging path [17, 18, 19]. The concept upon which the present analysis is based is complementary, as it should access both quark and gluon orbital angular momentum, depending upon the process which dominates the hard scattering.

We propose here a method to probe the spin-correlated transverse momentum of partons involved in hard collisions of longitudinally polarized protons leading to jet events at PHENIX. The basic picture is that if some part of the transverse momentum of partons is correlated to the (longitudinal) spin direction, as it would be in the case of orbital angular momentum, then hard collisions involving these rotating partons may lead to jets with more or less average transverse momentum k_T, depending upon the relative orientation of the spin directions and the centrality of the collision. Since, at present, there is no good experimental tool to determine the collision centrality in $p+p$ collisions, one must determine if the effect remains when the impact parameter is undetermined. In [1], with a rather simple picture of the transverse spatial and momentum distributions, it was found that by integrating over the impact parameter, a net overall effect is still found.

In PHENIX, due to our limited acceptance, we cannot measure the true jet axis as a direct way to measure the pair transverse momentum. An alternative method has been developed [2] that examines the π^0-hadron azimuthal angle correlation to extract the average pair transverse momentum on a statistical basis for two subsets of the data - like helicity collisions and unlike helicity collisions. The extracted average transverse momentum k_T for the two sets are compared as a measure of the helicity dependence of the interacting parton transverse motion.

The azimuthal correlation function is obtained by measuring the distribution of the azimuthal angle difference, $\Delta\phi = \phi_t - \phi_a$, between π° (triggered particle) and charged hadron (associated particle). Whenever a π^0 is found in the event, the *real* ($dN_{real}/d\Delta\phi$) and *mixed* ($dN_{mix}/d\Delta\phi$) distributions are accumulated. Mixed events are obtained by pairing a π^0 in an event with $h^\pm$ from a different event which is randomly selected. Figure 1 shows real and mixed event distributions for $3.5 < p_{Tt}(\pi^\circ) < 4.5$. Note that the associated hadron transverse momentum bin is fixed to $1.4 < p_{Ta}(h\pm) < 5.0$ through out this analysis.

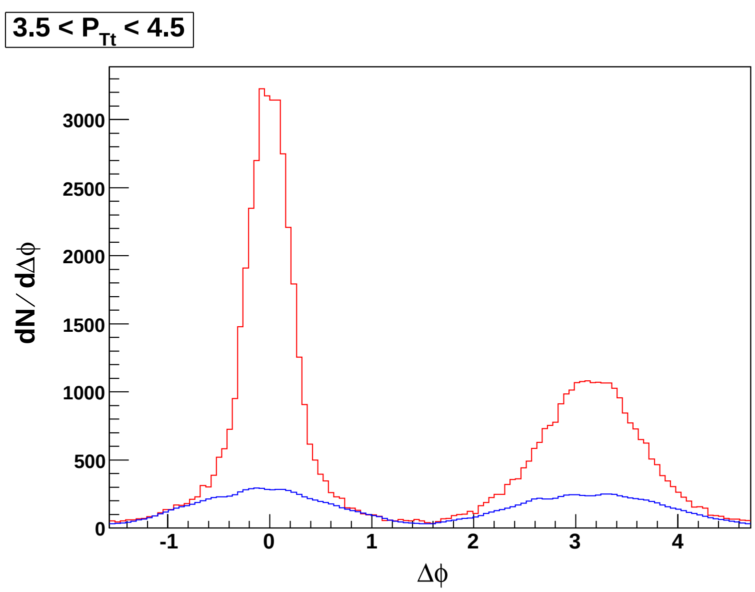

FIGURE 1. *red*: $dN_{real}/d\Delta\phi$, *blue*: $dN_{mix}/d\Delta\phi$

The jet fragmentation transverse momentum j_T and the partonic transverse momentum

k_T can be extracted from the widths of the peaks in the correlation function. However, as explained in [2] the raw $dN_{real}/d\Delta\phi$ distribution are fit with the following function to obtain σ_{near} and $\sqrt{\langle p_{out}^2\rangle}$ which are then used to extract j_T and k_T:

$$\frac{dN_{real}}{d\Delta\phi} = \frac{1}{N}\frac{dN_{mix}}{d\Delta\phi}\cdot\left(C_o + C_1\cdot Gaus(0) + C_2\cdot\frac{dN_{far}}{d\Delta\phi}\bigg|_{\pi/2}^{3\pi/2}\right) \tag{1}$$

where

$$\frac{dN_{far}}{d\Delta\phi}\bigg|_{\pi/2}^{3\pi/2} = \frac{-p_{Ta}\cos\Delta\phi}{\sqrt{2\pi\langle p_{out}^2\rangle}Erf\left(\sqrt{2}p_{Ta}/\sqrt{\langle p_{out}^2\rangle}\right)}exp\left(-\frac{p_{Ta}^2\sin^2\Delta\phi}{2\langle p_{out}^2\rangle}\right) \tag{2}$$

To check the possible systematic errors, bunch shuffling method was used. In bunch shuffling, we randomly flip the beam polarization signs for each event with a 50% probability, and then obtain the $\Delta\phi$ distributions for the two helicity combinitaions. The mixed event background is obtained from the whole data disregarding the helicity, and is kept the same for both helicity combinations. Since the mixed event background is used to correct the correlation function for effects of limited PHENIX azimuthal acceptance and for the detection efficiencies, we don't expect it to change with helicity. The results of the bunch shuffling indicate that the quoted errors on the fit parameters are correct, in that random grouping of the datasets and subsequent extraction of the fit parameters give results that fluctuate with widths given by the errors on the fit parameters. It should be noted that these errors are not, strictly speaking, statistical.

To calculate $\langle j_T\rangle$ and $\langle k_T\rangle$ from $\sigma_{near}\pm\delta\sigma_{near}$ and $\sqrt{\langle p_{out}^2\rangle}\pm\delta\sqrt{\langle p_{out}^2\rangle}$ values obtained from the fit, we followed [2], with a parameterization of $\langle z_t\rangle$ and $\hat{x}_h$ from values give in table XI of [2]:

$$\hat{x}_h\left(p_{Tt}\right) = a_o + \frac{a_1}{p_{Tt}^{a_2}} \tag{3}$$

$$\langle z_t\rangle\left(p_{Tt}\right) = a_o + a_1 p_{Tt} + a_2 p_{Tt}^{a_3} \tag{4}$$

Since any spin dependent effect should scale with the polarization of each beam, all helicity differences are scaled by the run-averaged beam polarization in the blue and yellow beams, both taken to be 0.47.

We first look at the difference for the calculated value of j_T. Some thought should be given to wether or not the fragmentation transvserse momentum should have any helicity dependence, however, in our model, we would expect no helicity combination difference. If we also assume no p_{Tt} dependence, so that we just take the average of our values, then the average value for j_T is 32 ± 24 MeV/c.

Next, we look at the k_T helicity combination differences and find $\Delta\sqrt{\langle k_T\rangle} = 672\pm 387$ MeV/c to be large, but with limited statistical significance (Figure 2).

Recently the STAR experiment has reported preliminary results on the Boer-Vogelsang effect that showed a zero left-right asymmetry implicating that the Sivers function in central rapidity is small. A non-zero Sivers function requires both orbital motion *and* either a final- or initial-state interaction. However, at least in the semi-classical

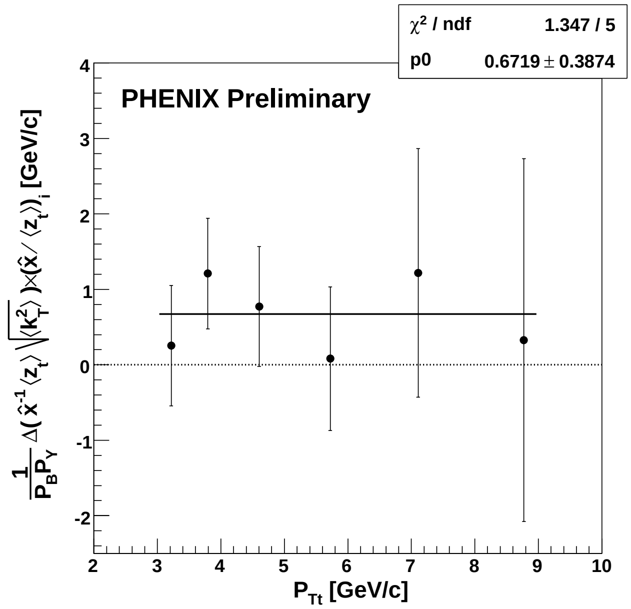

FIGURE 2. Difference in $\sqrt{\langle k_T^2 \rangle}$ (like- minus unlike-helicity combinations).

model in which this is framed, the k_T asymmetry does not require a final- or initial-state interaction. and can thus be seen as a complimentary probe to the Boer-Vogelsang measurement.

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